In Search of a Permanent Electric Dipole Moment of ^{199}Hg

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Outline

- **Introduction to EDMs**
  - Theoretical implications
- **Experimental Overview**
- **False Signals**
  - Completed improvements
  - Future work

What Is a Permanent Electric Dipole Moment (EDM)?

- A dipole, very simply, is a positive charge q and negative charge $-q$ that are separated by a small distance $\mathbf{r}$.

- The electric dipole moment $\mathbf{d}$ is given by :
$$\mathbf{d} = q\mathbf{r}.$$

- The EDM of a neutral particle would necessarily lie along its spin axis because all the other components would cancel.

Violating T and P Symmetry

- Reversing time (going from **a** to **c**) changes the spin of the particle.

- Switching the spatial coordinates (going from **a** to **b**) swaps the charges.

- By the CPT theorem, if T is violated, then CP is also violated.
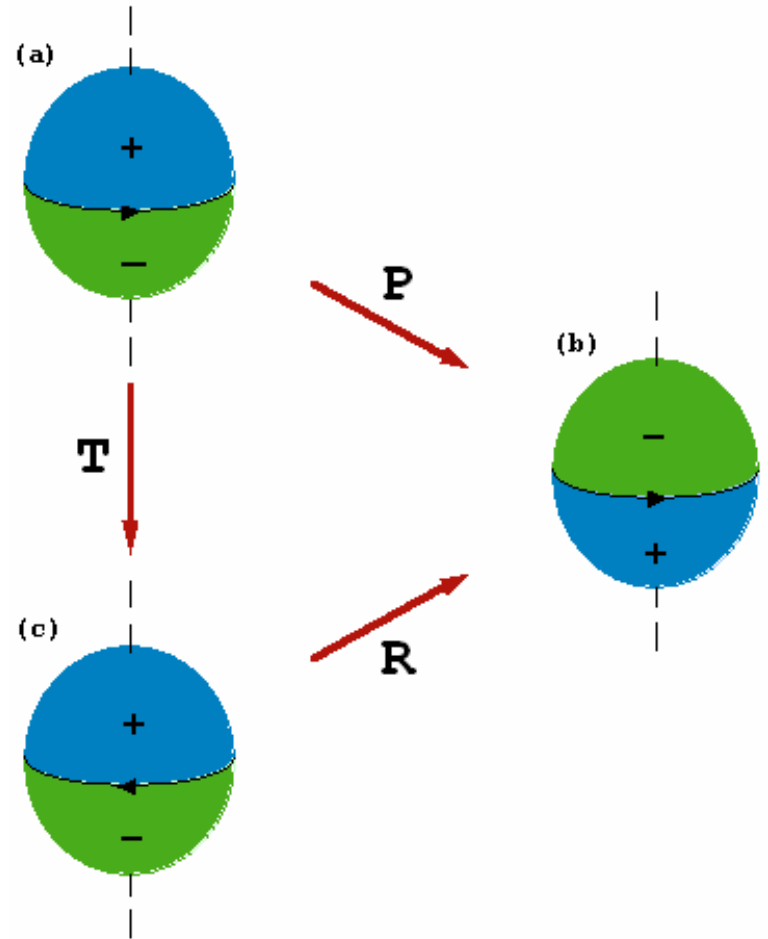
Implications of CP violation

- Believed to be responsible for the matter-antimatter asymmetry in the universe →Should be more common.

- The decay of K^0 and B mesons confirm CP violation experimentally.

- EDM experiments are part of search for new sources of CP violation.

- The Standard Model contains a mechanism for handling the CP violations that occur with EDMs, but the EDMs predicted are negligibly small.

- One of the possible extensions of the standard model, Supersymmetry, predicts EDMs that are much larger and within current experimental limits.

Background Theory
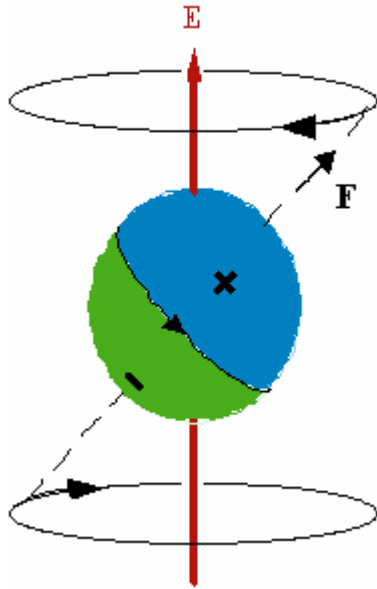
- Basic idea: Apply an electric field E and a magnetic field B to the sample and then look for effects.
- The Hamiltonian (total energy) of the system is:

$$H = -(\mu B + dE) \cdot \frac{F}{|F|},$$

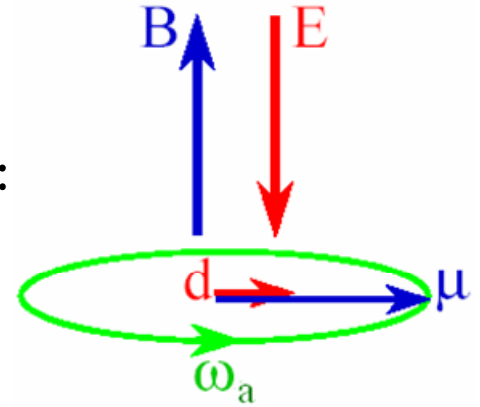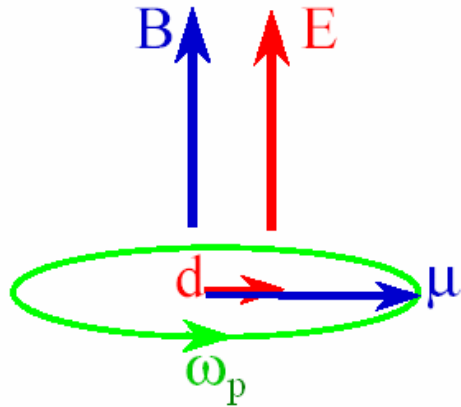where μ is the magnetic moment, d is the dipole moment, and F is the total angular momentum.

- F will rotate at the Larmor precession frequency because μ feels a torque due to B.

- This frequency, measured when E and B are parallel and antiparallel, is used to find EDMs.

- In the parallel case, the Larmor frequency is given by:

$$\omega_p = (\mu B + dE)/(\hbar F),$$

and the antiparallel case is:

$$\omega_a = (\mu B - dE)/(\hbar F).$$

- Thus, if we calculate the difference between the two measured frequencies, we can determine *d*:

$$\Delta\omega = \omega_p - \omega_a = \frac{2Ed}{F\hbar}.$$

- Atoms, like ^{199}Hg, with nuclear spin ½ and no net electronic spin are less susceptible to some undesirable systematic effects. We can replace *F* in the above equation with ½, giving us:
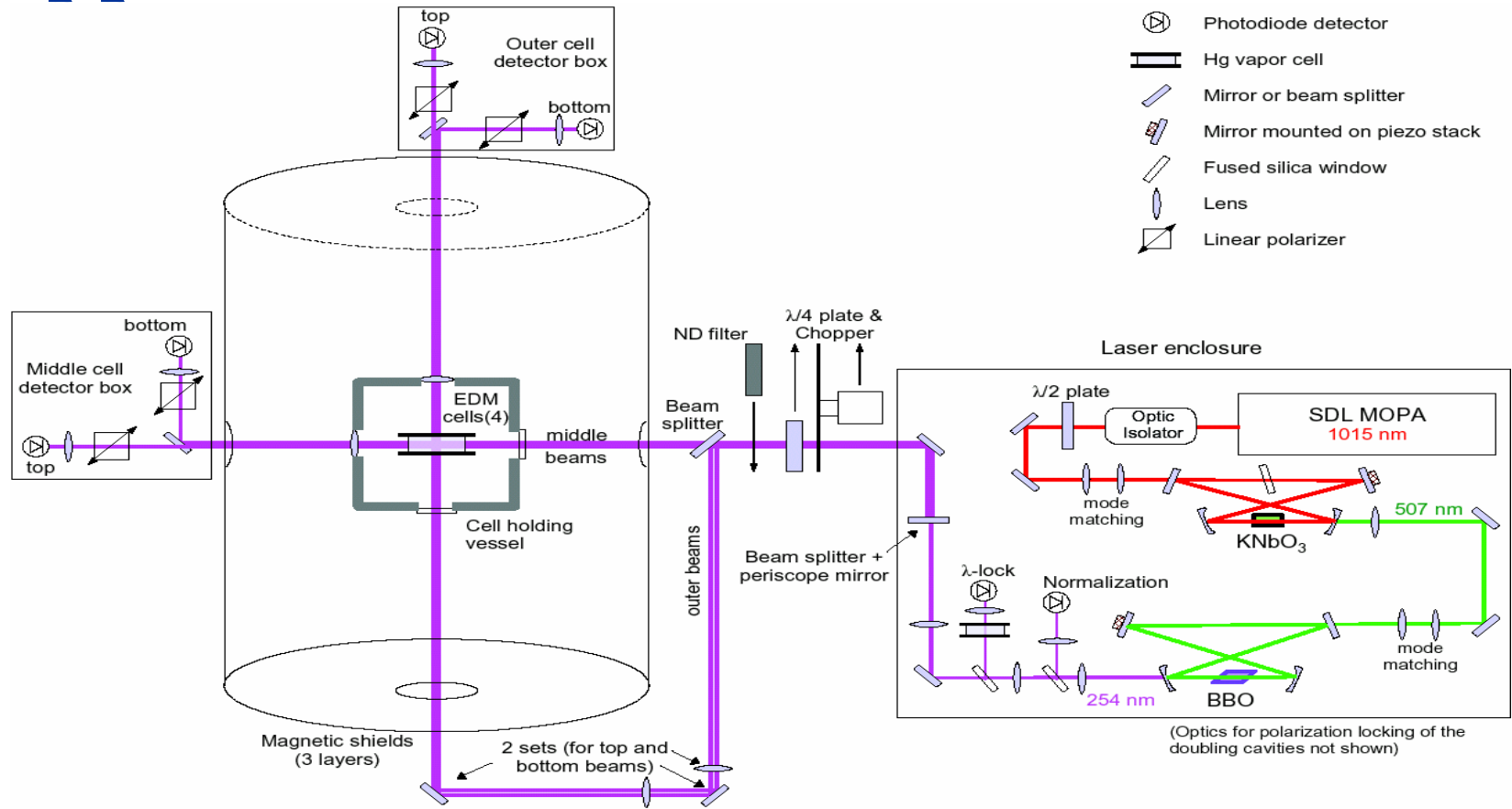
$$\Delta\omega = \frac{4Ed}{\hbar}.$$

Experimental Setup

- When looking at the apparatus used to detect EDMs, there are two main sections, the "pink elephant" and the laser cavity:
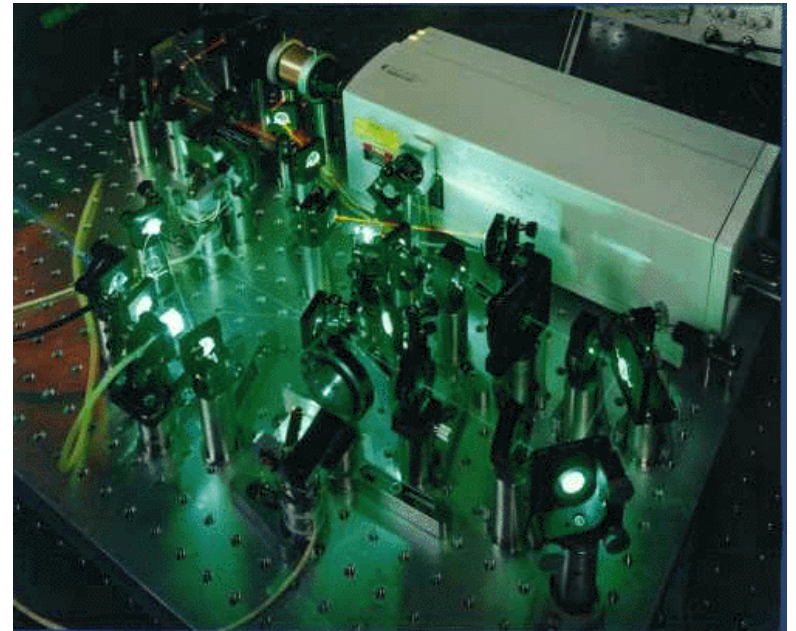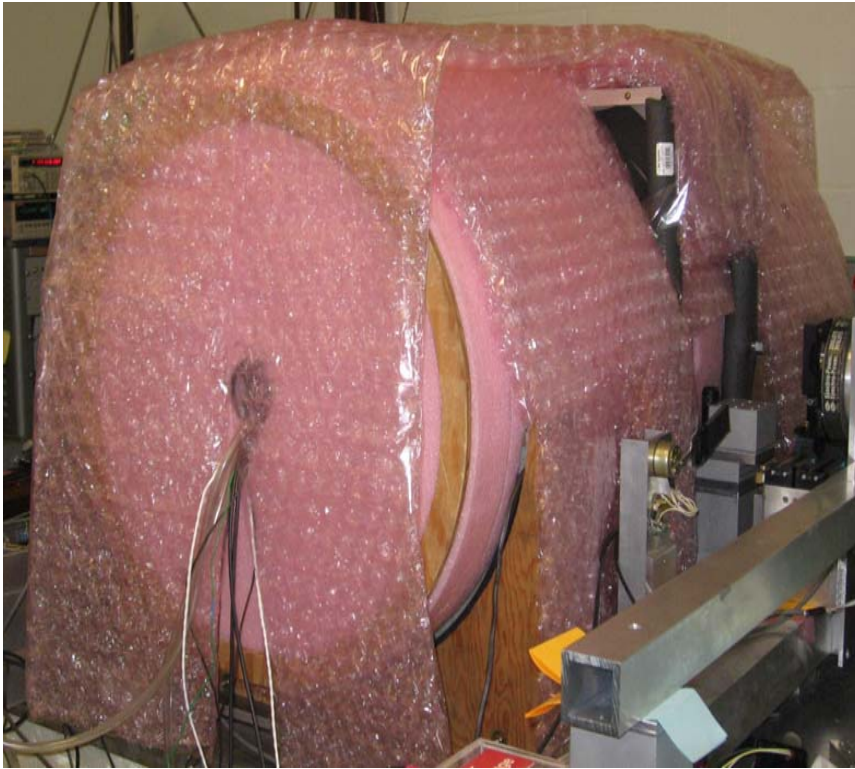
Apparatus Schematic

Above is the entire apparatus. The "pink elephant" section is the large cylinder on the left and the laser cavity is on the right.

Optical Pumping

- ^{199}Hg atoms have $\pm\frac{1}{2}$ nuclear spin. Must align them one way.

- A circularly polarized ultraviolet laser with $\lambda=254$ nm excites a transition in only spin $-\frac{1}{2}$ atoms, which can then relax into either spin state.

6^3P_1 _____   _____

254 nm σ^+

6^1S_0 _____   _____

$m_f =$ $-\frac{1}{2}$ $\frac{1}{2}$

- An infrared laser with $\lambda=1016$ nm goes through two frequency doubling cavities to output an ultraviolet laser.

- The laser beam passes through a $\lambda/4$ wave plate to circularly polarize it and an optical chopper rotating at the Larmor frequency.
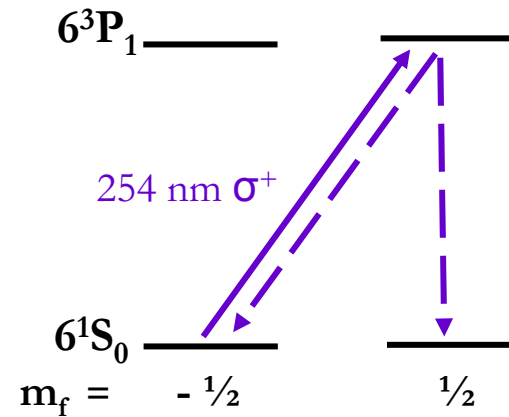
Inside the Elephant

- Four quartz Hg vapor cells inside three layers of magnetic shielding.

- Two inner cells are sandwiched between the outer cells and a central gold-plated ground plane.

Outer, magnetometer cells

Inner cells

Gold-plated ground plane

High voltage electrode

H V

H V
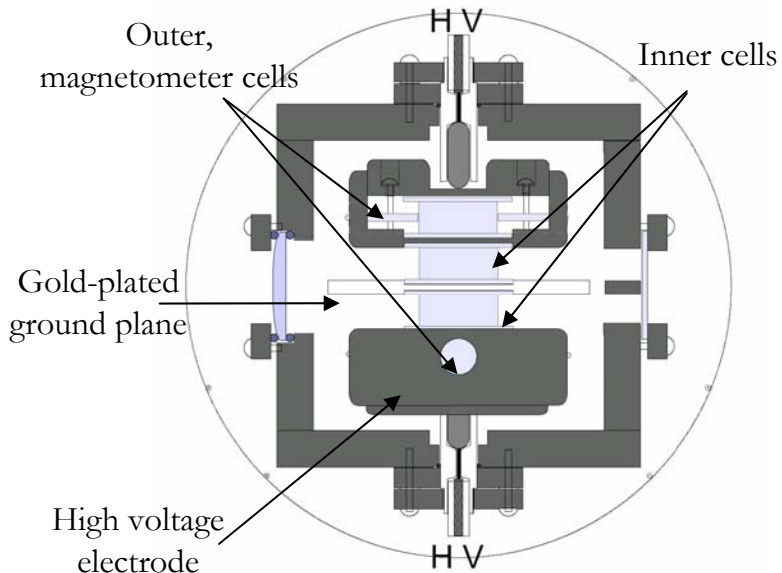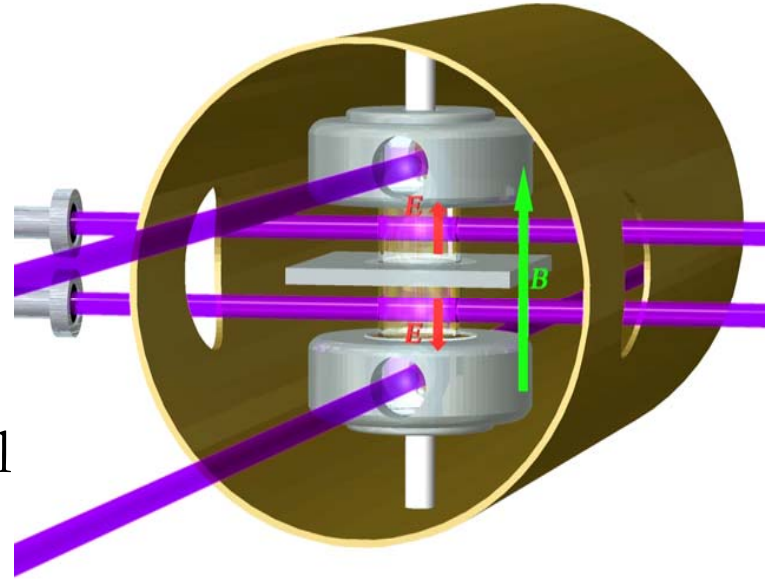
- The two outer cells sit inside the high voltage electrodes, act as magnetometers.

- Same B-field for all cells.

- The *E*-field points in opposite directions in inner cells (no E-field in outer cells).

Hg vapor cells

- The vapor cells also contain 475 Torr of CO, used to help the Hg atoms hold their spin polarization longer.

Paraffin

100 % CO

^{199}Hg

Mercury

Synthetic Quartz

Paraffin coating

- Insides of the cells are coated in paraffin, also extends spin relaxation time.

- Circularly polarized laser light is split into two beams that pass through the inner two cells.

- Once the pumping stage is complete, the laser is switched to being linearly polarized for the probing stage.
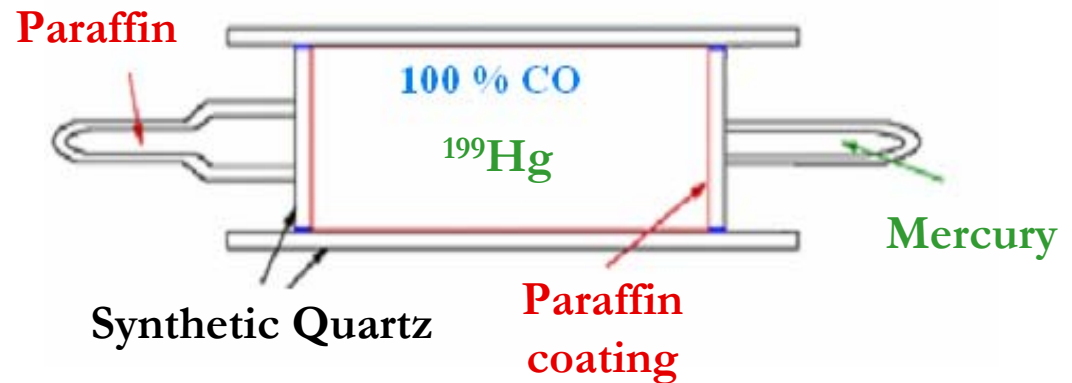
Optical Probing
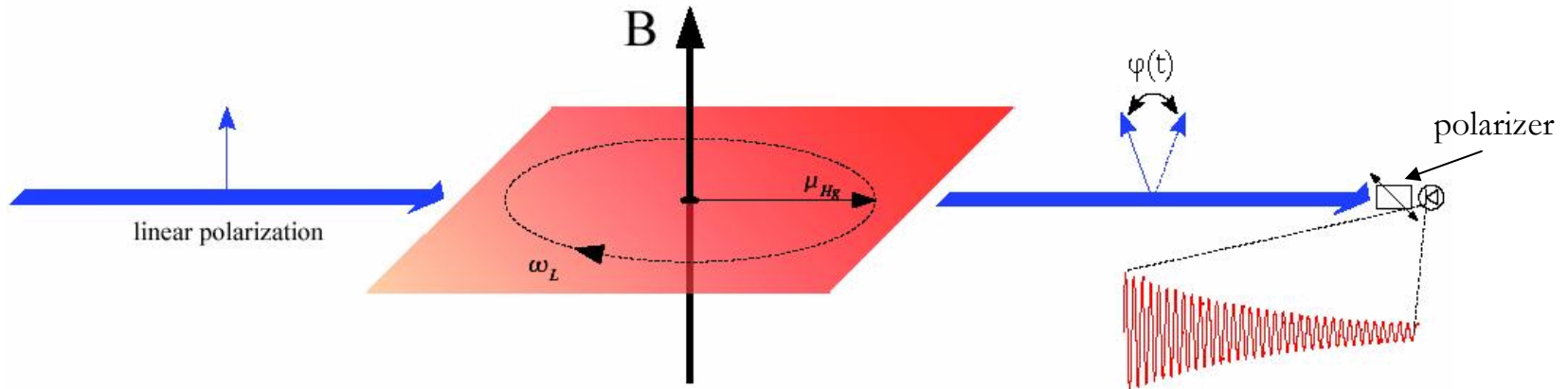
- Linearly polarized laser light passes through the cells and is rotated by angle:

$$\varphi(t) = \varphi_0\, e^{-t/\tau} \sin \omega t,$$

where τ is the beam coherence time.

- In order to measure φ, must measure the intensity:
$I = I_0 \sin 2(\alpha + \varphi(t))$,
where α is angle of polarizer, relative to non-rotated light.
- Intensity decreases exponentially as it varies sinusoidally.

Previous Results

- When the experiment was last operational, it was sensitive to EDMs with $d(^{199}\text{Hg}) < 2.1 \times 10^{-28}$ e cm.

  → If the Hg atom was the size of the Earth, they could detect a 0.001 angstrom bump in the charge distribution at the north pole.

- Even with this level of sensitivity, no EDMs have been found to date, in this lab or any others.

- Unfortunately, a long search for the source for false signals has prevented any new data from being collected recently.

False Signals

- False signals of varying sign and magnitude began in 4-cell vessel.

- Showed up more often after apparatus had been open.

- Most likely due to small spark that magnetizes some material $\rightarrow$ greater B-field (in same direction as applied B-field) increases Larmor frequency like an EDM would.
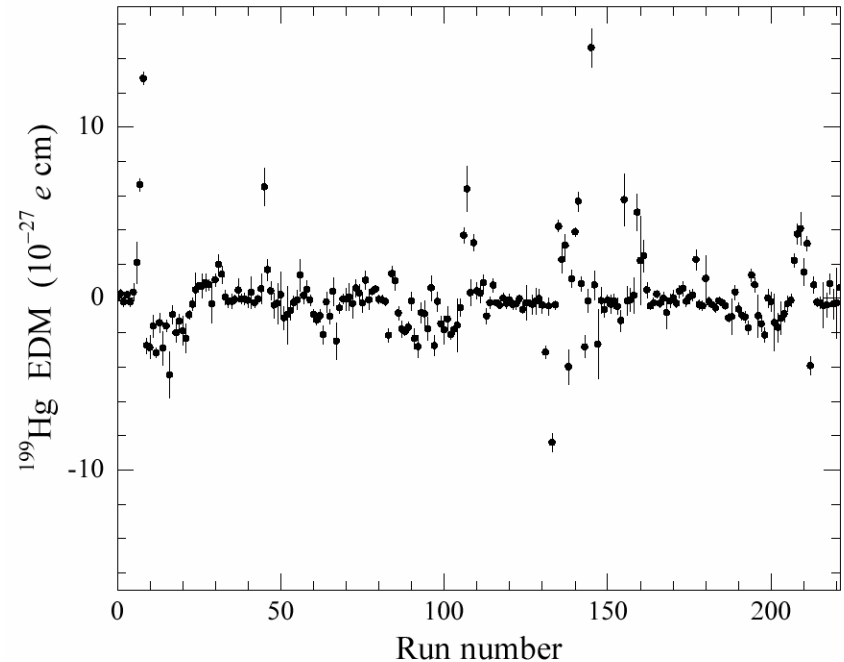
Working to reduce problems

- Reducing possible materials inside that can be magnetized should eliminate problem.
  - All materials have been tested for magnetic properties.
  - Questionable materials have been replaced.
  - Old insulation was replaced for fear that its dust was magnetic.
  - All parts of the apparatus have been meticulously cleaned.

General Improvements

- Other improvements have been made to overall apparatus.
    - Less noisy wavelength lock was built for laser.
    - Metal photodiode shields were replaced with plastic ones.
    - New and improved ground plane was installed
    - High voltage cable and supply replaced.

Future Work

- Still looking for non-ferromagnetic conductive paint for cells.

- When all current work and cleaning are complete, 4-cell vessel will be reinstalled.

- New EDM data will be taken to see if improvements have eliminated false signals.

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